Computers and Geotechnics 80 (2016) 59–70

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

# A study on the draw laws of caved ore and rock using the discrete element method

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ARTICLE INFO

*Article history:*
Received 25 January 2016
Received in revised form 23 June 2016
Accepted 26 June 2016

*Keywords:*
Caved ore and rock
Draw law
Physical draw experiment
Numerical draw simulation
Isolated extraction zone
Discrete element method

ABSTRACT

Isolated physical draw experiments are conducted to investigate the shape of the isolated extraction zone (IEZ) and its main influencing factors. After validating the reliability of using Particle Flow Code (PFC) for draw simulation, various numerical models are constructed to investigate the draw laws of caved ore and rock under multiple drawpoint conditions. The results show that particle size, drawpoint size and column height have negligible effects on the IEZ's shape, which is mainly controlled by mass drawn, and that the ore loss ratio decreases with increasing drawpoint size and caved ore layer height and increases with increasing drawpoint spacing.



## 1. Introduction

The caving mining method has been widely used in metal mines around the world. In China, more than 85% of iron ores and approximately 40% of non-ferrous metal ores in underground mines are drawn using this method. Approximately 25% of mines across the world use this method. A characteristic of the caving mining method is that caved ores, surrounded by overlying rocks, are drawn from the drawpoint. Therefore, ore loss and dilution rates are generally large. Inappropriate draw process management or an unreasonable stope structure design will cause the waste of mineral resources and a decrease of economic benefits for mining enterprises [1]. During the mining of large-scale underground metal ore deposits using the caving method, the draw laws of the caved ore and rock are related to the shapes of the isolated extraction zone (IEZ) and the isolated movement zone (IMZ), the shape and position of residual ores, and the movement of the ore waste interface. Moreover, different properties of granular particles, boundary conditions, stope structural sizes and draw modes directly affect the caved ore and rock draw laws, as well as ore recovery indices, such as the loss and dilution rates. Therefore, a large number of research studies has focused on the draw laws of caved ore and rock.

Conventional draw laws are based on ellipsoid draw theory [2] and random medium draw theory [3]. Ellipsoid draw theory is primarily based on realistic mining situations under the infinite boundary condition and has dominated draw analysis in the caving method because of its practical applicability. Random medium draw theory is also widely used in practice because the equations of particle movement velocity, particle movement trace and the IEZ's shape, which are deduced from a probability density function of granular particle movement, have been shown to be very efficient and able to provide results that are consistent with the results of physical experiments. Therefore, it has also been widely used in practice.

Physical experiments are critical to research on draw, and a large number of investigations have been conducted. For example, Tao et al. [4] and Wang et al. [5] performed draw experiments to study the influence on flow characteristics of caved ore and rock of important factors such as particle size, drawpoint size, and water content. Wu [6] studied the draw behavior of granular particles under multiple drawpoint conditions using similarity simulation and determined the effect of adjacent drawpoints on the draw process. The above research results are significant for the design of stope structural parameters and for improving

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http://dx.doi.org/10.1016/j.compgeo.2016.06.016
0266-352X/

economic performance. Moreover, many laboratory draw experiments with sand or gravel as the medium were conducted to provide more insight into the flow behavior and mechanism of caved ore and rock [7–14], which promoted rapid research development in this field.

Numerical simulation techniques have also been increasingly and widely applied to the study of draw [15–21]. Based upon the finite difference method (FDM), the finite element method (FEM), the discrete element method (DEM), the theory of cellular automata (CA), or fluid mechanics, draw models and software have been applied and developed. The DEM uses Newton's second law to establish the relationship between particle movement and the forces causing this movement [22]. Two or more particles interact through normal and tangential forces at a contact point or contact surface. The Particle Flow Code (PFC) [23] is a commercial numerical software that has been developed based on the theory of mesoscopic discrete elements (particle element theory) and is mainly employed in the study of fundamental problems, such as the basic characteristics of rock materials, the deformation and failure mechanisms of rock media, and the dynamic responses of granular particles. Using PFC software to conduct draw simulations and select draw schemes is convenient and flexible and allows repeated simulations to be conducted. Additionally, the flow behaviors of caved ore and rock considered as particulate materials can be analyzed from a mesoscopic point of view [23,24], and the process of movement, recycling, residual of ore and mix of waste can be clearly described. Based on PFC$^{3D}$, Lorig, Cundall and Pierce [25–27] conducted a large number of numerical draw simulations and developed the REBOP (Rapid Emulator Based On PFC3D) program [13], which can quickly simulate the draw process. REBOP requires calibration of erosion and collapse coefficients to determine the IMZ; it also requires that the velocity profile be adjusted to obtain the IEZ. Calibration could be carried out by adjusting simulation results from either scaled physical models or full-scale trials, which makes REBOP better than a number of current rule-based mixing models because the flow pattern is modeled [13]. Moreover, Wu et al. [28], An et al. [29] and Zhang [30] conducted numerical research on draw methods and the optimization of stope structural parameters of the Jinshandian Iron Mine, Meishan Iron Mine and Shouyun Iron Mine, respectively.

There has been a large number of physical experimental studies on draw, but there have been few reports on systematic and comprehensive numerical investigations on the draw laws of caved ore and rock that include change trends of the IEZ's shape and its influencing factors under isolated and multiple drawpoint conditions, the influence of different structural parameters and draw modes on dilution and loss indices, etc. Because physical draw experiments are time-consuming, laborious, and lack reproducibility, in this paper, isolated physical draw experiments are first carried out to investigate the IEZ's shape and its main influencing factors. Numerical draw simulations using the PFC$^{3D}$ code are then conducted under the same conditions as the physical draw experiments. Qualitative and quantitative comparison and analyses between the physical draw experiments and the numerical draw simulations are performed and the reliability of the draw simulation of caved ore and rock using the PFC code is validated. Subsequently, various draw models are constructed to investigate the draw laws of caved ore and rock under multiple drawpoint conditions. The proposed draw numerical method can enrich and improve existing draw laws in an explicit manner. It prompts draw research, especially numerical draw simulations that are a beneficial supplement to physical and in-situ draw experiments. It can also play an important role in mining design and production management by optimizing structural parameters and draw control, forecasting dilution and loss indices.

## 2. Influencing factor analysis of IEZ draw laws

### 2.1. Physical experiments of isolated draw

#### 2.1.1. Experimental model and materials

As shown in Fig. 1, a self-designed physical model of geometrical scale 1:100 was utilized in the isolated draw experiments. The size of the model was 500 mm × 500 mm × 1200 mm (length × width × height), and the drawpoint was located in the center of the model's base so that the flow zones did not intersect with the model's walls. The materials and labeled markers used in the tests were magnetite ores from the Meishan Iron Mine (Fig. 2). The ore solid density was 3700 kg/m$^3$, and the waste rock solid density was 2700 kg/m$^3$. The material of ore or rock was cohesionless and had a friction angle of 42° when tested under conditions similar to those in the model. The model wall friction angle was calculated to be approximately 26.5°.

#### 2.1.2. Experimental processes

There are many factors that affect the draw laws of caved ore and rock, including column height, caved ore and rock sizes and their characteristic parameters (for example, internal friction angle, cohesion and coefficient of the volumetric expansion), and drawpoint size [4]. Fig. 3 shows the main parameters of IEZ and IMZ, in which $h_{IEZ}$, $h_{IMZ}$ and $w_{IEZ}$, $w_{IMZ}$ are the heights and widths of the IEZ and IMZ, respectively.

To study the flow characteristics of the IEZ, the influencing factors mainly considered in this paper are particle size, drawpoint size and column height. Nine orthogonal tests [31] with respect to these three factors and three levels for the IEZ's height were designed. In each test, mass drawn $m$ at different IEZ's heights $h_{IEZ}$ was recorded. The designed test parameters are shown in Table 1.

The labeled markers were distributed radially every 50 mm in the height direction. As shown in Fig. 4, the adjacent two rows of labeled markers were at an angle of 30° and two adjacent labeled markers in the same row had a spacing of 40 mm. Each labeled marker was regarded as a coordinate point in the model. A certain amount of ore was drawn from the drawpoint each time, and the number of labeled markers drawn was recorded. The draw processes terminated when the IEZ' height reached 800 mm.

#### 2.1.3. Analysis of experimental results

Through weighing the mass drawn and recording the number of labeled markers drawn each time, the IEZ's shape could be delimitated using an interpolation method; then, the relationship between the IEZ's height and the mass drawn could be determined. To study the effects of the three factors (particle size, drawpoint size and column height) on the shape of the IEZ and the difficulty degree of the draw, this investigation employed a statistical approach to process data based on the IEZ's delimitated shape. Significance tests of the IEZ's width at different heights of the IEZ were employed, with 95% fiducial probability. The analysis results showed that within the range of values considered, the three factors (particle size, drawpoint size and column height) did not significantly affect the IEZ's shape.

### 2.2. Numerical simulations of isolated draw

Physical experiments are time-consuming, laborious, and lack reproducibility. Therefore, it is necessary to adopt a simpler and more efficient way to replace physical experiments. Based upon particle flow theory, particulate materials can be analyzed from a mesoscopic point of view by using PFC software, which is convenient and flexible and allows repeated simulations to be conducted. The particle-based numerical method is expected to be